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Searches for long-lived particles, lepton-jets, stable and meta-stable particles with the ATLAS detector

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Abstract

Several proposed extensions to the Standard Model, such as certain supersymmetric scenarios, predict new phenomena such as long-lived particles and sectors of hidden particles. Long-lived particles can lead to a wide variety of detector signatures depending on the nature of the particle and the decay length, such signatures include: displaced vertices; disappearing tracks; massive particle tracks; and jet production outside of collision event windows. Hidden sectors may additionally lead to the production of collimated jets of leptons. Recent searches for such signatures at ATLAS are presented here. There have been six analyses performed using 8 TeV data, four 7 TeV data analyses are also included for completeness. No evidence of any new physics is observed in any analysis, all use their results to set limits on supersymmetric or hidden valley models.

Keywords:
ATLAS, SUSY, HV, LLP, lepton-jet

1. Introduction

Some proposed theories beyond the Standard Model (BSM) can lead to the production of unusual signatures in detectors at the Large Hadron Collider (LHC). These may include: long-lived particles (LLPs); meta-stable particles; collimated jets of leptons.

The ATLAS Collaboration has recently published several new results on searches for these signatures. Here, an overview is given of the theoretical motivations, followed by the search methods and results of recent analyses. All quoted limits on models are at the 95% confidence level.

2. The ATLAS detector

The ATLAS experiment is one of two general purpose detectors on the LHC. It is designed to be able to reconstruct events from many different physics processes and can be used to investigate a variety of physical theories.

ATLAS can be briefly described as having four concentric detector systems. From the innermost system outwards: the inner detector (ID) tracks charged particles near the beam crossing with sufficient accuracy to reconstruct primary vertices; the electromagnetic calorimeter (EMcal) stops electrons and photons, measuring their energy; the hadronic calorimeter (Hcal) stops most strongly interacting Standard Model (SM) particles, measuring their energy; the muon spectrometer (MS) reconstructs charged tracks outside of the calorimeter system. Magnetic fields generated by a solenoid surrounding the ID and a toroidal system interspersed with the MS allow track momentum to be measured. Further information on ATLAS can be found in reference [1].

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3. Theoretical motivations

The analyses described here are interpreted in two types of theoretical frameworks: Supersymmetry (SUSY) models and Hidden Valley (HV) models. LLPs may be produced in either of these frameworks. Lepton jet signatures generally require HV models; a supersymmetric one has been considered here.

3.1. Supersymmetry

SUSY posits the existence of superpartners for all SM particles and is a popular potential solution to the hierarchy problem. Decay of SUSY particles exclusively to SM particles is prevented by R-parity, although both R-parity violating (RPV) and conserving (RPC) models are proposed. Both RPV and RPC SUSY models can give rise to LLPs, although the origin of the LLP lifetime is subtly different in each case [2].

In RPV SUSY, the LLP is typically the lightest SUSY particle (LSP). The decay of the LSP is suppressed by a weak coupling to SM particles and results in an LSP with a measurable lifetime.

In RPC SUSY, the LLP is the next to lightest SUSY particle (NLSP). The decay of the NLSP to the LSP is suppressed either by weak coupling, or a mass degeneracy. The LSP is then completely stable, but must be undetectable due to cosmological considerations.

Both of these scenarios can have a wide range of LLP lifetimes. The LLP can be charged or neutral and decay through either hadronic and leptonic processes. This diversity leads to rich phenomenological possibilities at detectors.

3.2. Hidden Valley models

In HV models there exists a sector that couples very weakly with the SM. A particle from this sector can be produced in certain weak interaction decays, such as that of the Higgs boson, with the behaviour of the produced particle determining the signature.

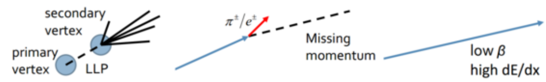
If the particle itself couples weakly to the SM then it may travel some distance before decaying into SM particles. This makes the particle a neutral LLP and can give rise to displaced vertex signatures in the detector [3].

The particle may also produce a shower in the hidden sector [4, 5]. If dark photons (γ_D) are produced in these showers and couple to the SM, they may decay into highly collimated pairs of light SM particles, specifically e, μ or π. Multiple γ_D may be radiated by the same hidden sector particle, with the resulting overlapping γ_D leading to jets with multiple pairs of particles. Decays of γ_D to heavier particle pairs, such as protons, are kinematically forbidden. Highly collimated jets of leptons do not occur in the SM, and are the subject of BSM searches.

These two signature types from HV models are not mutually exclusive. The γ_D may be long-lived, which can result in jets of lepton pairs originating from displaced vertices.

4. Long-lived Particle Searches

LLPs are predicted by several BSM models and, if detected, would be a clear indication of new physics. The signature left by an LLP depends greatly on the scale of the decay length (fig 1) and the particle charge. As such, there are numerous analysis techniques aimed at discovering LLPs at ATLAS.



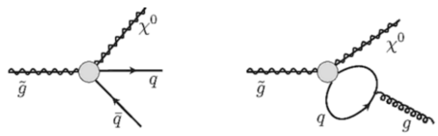
(a) $c\tau \approx 0.1 - 10$ m, displaced vertex (b) $c\tau \approx 0.1$ m, disappearing track (c) $c\tau > 1$ m, stable massive particle

Figure 1: Typical signatures of LLPs with different decay lengths ($c\tau$).

The six most recent LLP searches at ATLAS have been performed with 8 TeV data, taken during 2012. Two of the more recent 7 TeV (2011) analyses are also described here for completeness. No evidence of BSM physics was observed in any of the analyses and each uses its results to sets limits on SUSY or HV models. The search techniques and results of each analysis are summarised in the following sections.

4.1. 8 TeV *LLP analyses*

Of the six 8 TeV LLP searches at ATLAS, five are for SUSY LLPs [6, 9, 10, 12, 13] and one is for HV LLPs [11]. The Metastable Gluino [6] and Calorimeter Ratio [11] analyses were most recently completed and, as such, will be outlined in slightly greater detail. The analyses are introduced, approximately, in order of increasing decay length.



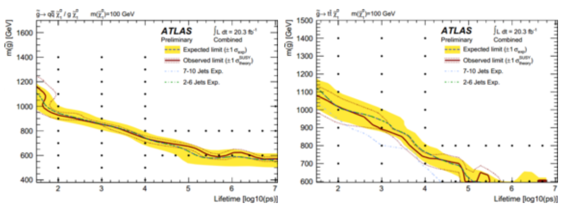
(a) $q\bar{q}$+$\tilde{\chi}^0$ decay path. (b) g+$\tilde{\chi}^0$ decay path.

Figure 2: Decays of long-lived $\tilde{g}$ in split SUSY [6].

The Metastable Gluino analysis [6] re-interprets two earlier searches for promptly decaying SUSY particles, in the context of split SUSY models with meta-stable $\tilde{g}$. The "7-10 jets" analysis [7] constructs 19 signal regions based on [7,8,9,≥10] jets, [0,1,≥] b-tagged jets and $E_{\mathrm{T}}^{\mathrm{miss}}$. The "2-6 jets" analysis [8] uses 15 signal regions based on [2,3,4,5,≥6] jets and $E_{\mathrm{T}}^{\mathrm{miss}}$. The decays of the $\tilde{g}$ in the new models (fig 2) can either be to $t\bar{t}+\tilde{\chi}^0$ if the $\tilde{t}$ is the lightest squark or to a combination of $q\bar{q}+\tilde{\chi}^0$ and $g+\tilde{\chi}^0$ if the squarks are mass degenerate. In the $q\bar{q}/g$ case only the "2-6 jets" analysis can be used to set limits due to the low jet multiplicity in that model. Although being re-interpreted to set limits on LLP models, the analyses do not use decay length as a handle. The reduced limit setting ability for larger $c\tau_{\tilde{g}}$ values visible in fig. 3 is due to a reduction in jet acceptance as production vertices leave the ID fiducial volume. Limits set by this analysis exclude $m_{\tilde{g}}$<900 GeV in the $t\bar{t}$ model and $m_{\tilde{g}}$<850 GeV in the $q\bar{q}/g$ model, for $\tau_{\tilde{g}}$=1 ns and $m_{\tilde{\chi}^0}$=100 GeV.

The Muon + Displaced vertex analysis [9] searches for $\tilde{\chi}^0$ decays to μ+jets at a displaced vertex. Vertices resulting from $\tilde{\chi}^0$ decays are identified by requiring them to have an associated muon with impact parameter $|d_0| > 1.5$ mm. The vertices must be reconstructed by the ATLAS tracker, which limits vertex displacement to the $r < 180$ mm and $|z| < 300$ mm fiducial region. The vertices are required to have reconstructed mass > 10 GeV to reduce background from other processes and > 4 tracks to reduce the effect of fake vertices. This analysis allows limits excluding production cross sections of $\sigma\times$BR $> 0.8 - 5.4$fb, depending on model parameters, to be set over a $c\tau_{\tilde{\chi}^0}$ range of order 100 mm to 10 m.

The Disappearing Tracks analysis [10] considers Anomaly Mediated SUSY Breaking models with mass degenerate $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^0$. $\tilde{\chi}^{\pm}$ traversing the detector may decay to a single $\tilde{\chi}^0$ and low energy $\pi^{\pm}$, $e^{\pm}$ in the ID, leaving a charged track that "disappears" at the decay vertex. These signatures are identified in the ATLAS ID by searching for isolated, high p_{T} (> 75 GeV) tracks that have well measured hits in the (inner) silicon trackers, but a low number of hits (< 5) in the (outer) straw tracker. Background in the signal region mostly comprises lower p_{T} tracks that have been mis-measured, with non-identified muons also contributing. Limits excluding $m_{\tilde{\chi}^{\pm}} < 270$ GeV are set by fitting a likelihood function to the p_{T} distribution of signal region tracks.



(a) $t\bar{t}$ model exclusion limits. (b) $q\bar{q}/g$ model exclusion limits.

Figure 3: Metastable Gluino analysis; exclusion limits against $\tau_{\tilde{g}}$ for $m_{\tilde{\chi}^0}$=100 GeV [6].

The Calorimeter Ratio analysis [11] uses a specialist trigger to search for long-lived neutral particles decaying in the calorimeter. The results are interpreted in the context of an HV model with a π_v LLP. The *CalRatio* trigger is tuned for narrow jets with high energy deposition in the (outer) HCal compared with the (inner) EMCal and no associated tracks in the ID. The analysis itself then re-enforces these trigger conditions offline by requiring two jets with $\log_{10}(E_{\mathrm{H}}/E_{\mathrm{EM}}) > 1.2$ (fig 4) and no good associated tracks with $p_{\mathrm{T}} > 1$ GeV in the ID. At least one of these jets must have been tagged by the *CalRatio* trigger and the leading jet must have $E_{\mathrm{T}} > 60$ GeV. Decay lengths of 0.37 m $< c\tau_{\pi_v} < 5.12$ m are excluded for $m_{\pi_v} = 25$ GeV and $m_{h_0} = 126$ GeV in the model considered.

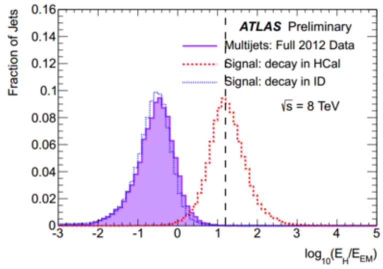


Figure 4: Calorimeter Ratio analysis; jet energy deposition ratio between the HCal and EMCal for SM jets in data and MC signal samples [11]. The $\log_{10}(E_{\mathrm{H}}/E_{\mathrm{EM}}) > 1.2$ threshold used by the analysis is shown by a dashed line.

The Long-Lived Slepton analysis [12] searches for charged LLPs with $c\tau > 1$ m with results interpreted in the context of a Gauge Mediated SUSY Breaking $\tilde{\tau}_1$. LLPs with $c\tau > 1$ m are likely to decay outside ATLAS and, if charged, leave a track similar to a muon throughout to detector systems. LLPs are differentiated from muons using track β values calculated from $\mathrm{d}E/\mathrm{d}x$ measurements in the ID pixel detectors and time-of-flight measurements in the Calorimeters and MS. Tracks are considered to be LLP candidates if they have $p_{\mathrm{T}} > 50$ GeV and $\beta < 0.95$. The background to this analysis is overwhelmingly high p_{T} muons with mis-measured β values. Background is reduced by requiring two LLP candidates in an event and the signal region is set by calculating candidate masses from their p_{T} and β, before applying a model dependant mass cut. For the model parameter range $\tan\beta = 5 - 50$, limits excluding $m_{\tilde{\tau}_1} < 402 - 347$ GeV can be set.

The Stopped R-Hadron analysis [13] considers the possibility of R-hadrons that lose all kinetic energy, stopping inside the calorimeter and then decaying outside of the event window. The search is performed by looking for jets in "Empty" bunch crossings, BCIDs with no protons in either beam. Background from cosmic rays is effectively suppressed by vetoing events with reconstructed muon segments. Excluding events with spike-like signals in the calorimeter rejects background from random electronic noise and also reduces the effect of cosmic rays and beam halo. The analysis requires events with an $E > 50$ GeV jet and no more than 6 jets in total, a requirement that the event $E_{\mathrm{T}}^{\mathrm{miss}}$ be more than half of the leading jet p_{T} is also applied. Depending on model parameters, limits excluding $m_{\tilde{g}} < 545-832$ GeV and $m_{\tilde{q}} < 344 - 397$ GeV can be set.

4.2. 7 TeV *LLP analyses*

Two of the most recent 7 TeV LLP analyses [14, 15] are included here for completeness as their search techniques are quite different to those of current 8 TeV analyses. Ref [14] interprets its results in the context of SUSY, while ref [15] uses the same HV model as the more recent Calorimeter Ratio analysis [11].

The Non-Pointing Photons analysis [14] searches for long-lived $\tilde{\chi}^0$ decays into $\tilde{G}+\gamma$ in a SPS8 Gauge Mediated SUSY Breaking model. The $\tilde{\chi}^0$ are produced in pairs, resulting in a final state with two high E_{T} γ from two different vertices and significant $E_{\mathrm{T}}^{\mathrm{miss}}$ carried away by the $\tilde{G}$s. The analysis requires two photon candidates in the EMCal, each with $E_{\mathrm{T}} > 50$ GeV, and for the event to have $E_{\mathrm{T}}^{\mathrm{miss}} > 75$ GeV. Limits are set by fitting templates of the expected signal γ z_0 distribution to that observed in data. The γ time of flight is also used as a cross-check on the z_0 results. Limits excluding $m_{\tilde{\chi}^0} < 230$ GeV are set by this analysis for $0.4 < \tau_{\tilde{\chi}^0} < 2.0$ ns.

The Muon RoI analysis [15] is similar to the more recent Calorimeter Ratio analysis [11], except that it uses a specialist trigger in the MS rather than the calorimeter. The Muon RoI trigger searches for jet-like clusters of Regions of Interest (RoIs), tagged by the ATLAS muon trigger. These clusters can be indicative of a secondary vertex between the outer edge of the calorimeter and the middle trigger layer of the MS. Background from punch-through jets and muon bremsstrahlung are reduced by requiring that the RoI cluster is isolated from $E_{\mathrm{T}} > 3$ GeV calorimeter jets and $p_{\mathrm{T}} > 5$ GeV ID tracks. The analysis requires two back-to-back, isolated, vertices to be reconstructed using a specialised MS tracking and vertexing algorithm, developed for this search. At $BR = 100\%$ and $m_{\pi_v} = 20$ GeV, decay lengths of $0.5\ \mathrm{m} < c\tau_{\pi_v} < 20.65$ m and $0.45\ \mathrm{m} < c\tau_{\pi_v} < 15.8$ m are set for a m_{h_0} of 120 GeV and 140 GeV respectively.

5. Lepton Jet Searches

Jets of tightly collimated leptons, if detected, would be an indication of new physics as such final states do not occur in the SM. Most recently, there have been two searches using ATLAS 7 TeV data. Both of these analyses interpret their results in the context of generic HV models with γ_D, produced in hidden sector showers, decaying into e or μ pairs. No evidence for physics beyond the Standard Model was observed in either of the analyses, both set limits on their respective HV models.

The Prompt Lepton Jet analysis [16] searches for lepton jets produced in a shower from the prompt decay of a light ($m < 2$ GeV) boson. The boson decays into $\tilde{q}$ pairs that decay into a shower in the hidden sector, producing the γ_D that lead to lepton jets. The energy and quantity of the leptons in the jets depend on γ_D mass and the dark sector gauge coupling constant α_d, with larger α_d resulting in more overlapping γ_D and hence more leptons in the jets. The analysis uses three channels, requiring an event to have: a single jet of ≥ 4 μ; two jets of ≥ 2 μ; or two jets of ≥ 2 e. The main background contribution is from the fake identification of lepton jets in hadronic multi-jet events. Limits set on the HV model considered exclude couplings of $\sigma\times\mathrm{BR} > 0.017-1.2$pb, depending on model parameters.

The Displaced Muonic Jet analysis [17] considers the case where the coupling of γ_D to the SM is suppressed to the extent that the γ_D has a measurable lifetime. The analysis is focussed on a HV model where the Higgs boson decays directly into hidden sector particles, that then produce a shower. As the γ_D are long-lived, overlapping decays cannot occur, resulting on only 2 leptons per jet. The MS is used to identify jets of highly collimated μ pairs that have zero total charge. Background from prompt processes is excluded by requiring the scalar p_{T} sum the jet ID tracks p_{T} ($\Sigma p_{\mathrm{T}}^{ID}$) be less than 3 GeV. Events are selected by requiring two such muon jets with high isolation and a separation between the jets of $|\Delta\phi| > 2$. Moderate limits on the jet impact parameters ($|d_0| < 200$ mm, $|z_0| < 270$ mm) is set to exclude contamination from cosmic rays. The remaining background mostly originates from multi-jet events and from secondary muon production in the decay of K, π etc. At a BR of 100%, decay lengths of $1 < c\tau < 670$ mm are set for $m_H = 100$ GeV and $1 < c\tau < 430$ mm for $m_H = 140$ GeV.

6. Summary

Long-lived particle and leptonic jet signatures, if observed, would be a clear indication of new physics. However, there has been no hint of such signatures in the searches conducted at ATLAS thus far. Analysis of these unusual signatures can be challenging to perform and work on the 8 TeV data collected during 2012 is ongoing.

Run-2 of the LHC represents new potential for discovery of new physics due to the increased energy and luminosity. Additionally, the new detector upgrades being installed at ATLAS may open new avenues to search for signatures of new physics.

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